

OPTICALLY AMPLIFIED RECEIVER

Field of the Invention

This invention relates to communication receivers, and more particularly, this invention relates to communication receivers that convert optical 5 communication signals.

Background of the Invention

The bandwidth of single channel (or wavelength) fiber optic telecommunication links is 10 mainly limited by the high-speed electronics required at the transmitter and receiver. Wavelength division multiplexing of optical communication signals is a technique used for increasing the bandwidth of a fiber optic telecommunications link, without increasing the 15 speed of the electronics. At the communications receiver, the optical channels that receive optical communication signals must be separated, or demultiplexed, and sent to their individual receivers, which vary in their rate of data receipt. One example 20 is 2.488 Gb/s receivers.

The demultiplexing process is not ideal and optical losses are incurred, thus reducing the overall receiver sensitivity. A reduction in sensitivity also translates into shorter transmission lengths for the 25 overall telecommunications link. When components are optimized on an individual basis, the benefits of any smaller size and lower power operation are not achieved with these type of receiver architectures. One current

method of achieving high sensitivities in a wavelength division multiplexed receiver is the use of a wavelength demultiplexer with avalanche photodiodes (APD). These electronically amplified optical 5 receivers have been designed as separate units in a rack-mounted configuration. Typically, each card unit within a rack-mounted configuration represents an individual component, forming a very large, but undesirable unit, especially in low power applications, 10 as in advanced aircraft designs or other design specifications where low power and small footprint are desired.

Because these types of optical receivers are rack-mounted units and use avalanche photodiodes, the 15 receiver sensitivity power penalty is incurred approximately equal to the optical insertion loss of the optical demultiplexer. Typically, telecommunications receivers using optical pre-amplification are not optimized for both high 20 sensitivity and low power, and are not contained within a single assembly. Also, in some optical communication receivers, a laser driver may be necessary. To deliver the current necessary to power a laser diode, an electric circuit is used and supplies power to the 25 laser driver, but also dissipates power of its own. This power, which is dissipated in the control circuit, is essentially wasted power, because it is not converted into photons.

Some current design injection laser diode 30 drivers use a linear pass transistor to deliver a regulated current to the injection laser diode. This method results in a constant voltage across the device and constant current through the device, resulting in a large amount of dissipated power. For example, nearly 35 90% of all power dissipated by the injection laser

diode driver occurs in the pass transistor, in some prior art designs. Thus, there is a necessary requirement and solution desired to deliver a clean current source to the injection laser diode.

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Summary of the Invention

It is therefore an object of the present invention to provide an optimized and fully integrated, high sensitivity, power efficient, optically amplified 10 receiver that is optimized as a system and incorporated into a single assembly.

It is still another object of the present invention to provide an optically amplified receiver that allows increased transmission distances over the 15 currently available technology, reduces the volume of valuable equipment-rack space, and provides more effective thermal management.

The present invention is advantageous and provides an integrated optically amplified receiver 20 that reduces power consumption and is beneficial for the large channel count and high data rate systems of modern communication systems. Noise performance of the receiver electronics can be traded with lower power operation. The receiver includes a high level of 25 integration and allows incorporation of common substrate thermal management. By designing the optically amplified receiver components to be optimized as a system and incorporating them into a single assembly, it is possible to increase transmission 30 distances over currently available technology, reduce the volume of valuable equipment-rack space, and provide more effective thermal management. The use of erbium-doped fiber amplifier technology also allows PIN detectors to be used in place of the avalanche 35 photodiode as the optical-to-electrical converter, thus

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increasing the overall reliability of the receiver to reduce power consumption.

The high receiver sensitivity and component reliability that is achievable with the optical 5 amplifiers and PIN detectors are integrated with customized low power pump laser drivers and receiver technologies to allow simplification and efficiency.

In accordance with the present invention, the optically amplified receiver includes an optical 10 preamplifier for receiving an optical communications signal over an optical communications line, which in one aspect of the invention, is a single optical communications line for receiving a wavelength division multiplexed signal. A bandpass filter is operatively 15 connected to the optical preamplifier and receives the optical communication signal, selects a single wavelength division multiplexed signal and filters out noise produced by the optical preamplifier. The optical preamplifier, in one aspect of the invention, 20 is a low noise, gain flattened, erbium doped optical preamplifier.

A laser driver is interfaced with a laser used to pump the optical preamplifier and includes an injection laser diode and a current source control loop 25 circuit connected to the injection laser diode that establishes a fixed current through the injection laser diode. A voltage switcher circuit is connected to the injection laser diode and current source control loop circuit. This voltage switcher circuit is adapted to 30 receive a fixed supply voltage and convert inductively the supply voltage down to a forward voltage to bias the injection laser diode and produce an optical output into the preamplifier having minimized power losses.

In yet another aspect of the present 35 invention, a demultiplexer filter is operatively

connected to the low noise, gain flattened, erbium doped optical preamplifier for demultiplexing the wave division multiplexed optical signal into a demultiplexed optical signal. A plurality of receiver 5 channels receive the demultiplexed optical signals. An optical-to-electrical conversion circuit is positioned within each receiver channel and converts the optical signals into electrical communication signals.

One of either a housing or circuit card 10 contains the optical preamplifier, laser driver, demultiplexer filter and optical-to-electrical conversion circuit as an integral receiver assembly. The bandpass filter is operatively connected to the optical preamplifier for receiving the optical 15 communication signal and filtering out noise produced by the optical preamplifier. This bandpass filter can comprise a tunable bandpass filter.

The optical-to-electrical conversion circuit can include a PIN detector and an amplifier circuit 20 connected to the PIN detector for amplifying the electrical communication signals. In yet another aspect of the present invention, the amplifier circuit can comprise an integration circuit, decision circuit and clock recovery circuit. In yet another aspect of 25 the present invention, the amplifier circuit can comprise a demodulator for analog transmission signals.

Brief Description of the Drawings

Other objects, features and advantages of the 30 present invention will become apparent from the detailed description of the invention which follows, when considered in light of the accompanying drawings in which:

FIG. 1 is a high level diagram showing an 35 example of a low-noise, wavelength division multiplexed

receiver of the present invention, connected to a star coupler and in-line, erbium doped, fiber amplifier repeater.

FIG. 2 is a block diagram of one example of
5 an optically amplified receiver of the present
invention.

FIG. 3 is a block diagram showing an example
of the laser driver/power converter of the present
invention, which is used as part of the optically
10 amplified receiver.

FIG. 4 is a block diagram showing an example
of a power splitter/optical bandpass tunable filter,
demultiplexer that can be used with the present
invention.

15 FIG. 5 is a schematic diagram of a power
splitter that can be used with the present invention.

FIG. 6 is a graph showing the bit error rate
versus input optical power in dBm, as an example of the
present invention.

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Detailed Description of the Preferred Embodiments

The present invention will now be described
more fully hereinafter with reference to the
accompanying drawings, in which preferred embodiments
25 of the invention are shown. This invention may,
however, be embodied in many different forms and should
not be construed as limited to the embodiments set
forth herein. Rather, these embodiments are provided
so that this disclosure will be thorough and complete,
30 and will fully convey the scope of the invention to
those skilled in the art. Like numbers refer to like
elements throughout.

The present invention provides a highly
engineered, optimized, and fully integrated, high
35 sensitivity wavelength division demultiplexed optically

amplified receiver that is designed to be used preferably with a single input fiber, having multiple wavelengths of communication signals. Also, the receiver allows significant power savings by using a 5 laser driver that has reduced power over many current state-of-the-art continuous wave laser drivers.

This power savings is accomplished by using a standard current source control loop configuration that is set to the desired current through an injection 10 laser diode. The current source has been optimized by using state-of-the-art components to minimize the amount of wasted power, i.e., power not delivered to the injection laser diode. The laser driver also has a current source that is a high efficiency variable 15 voltage switcher having an output voltage that is varied, such that there is minimal voltage drop across each of the components in the current source leg, thus wasting no excess power. These power savings can be diverted to other circuits in the system, and can allow 20 a battery powered device to last longer with increased financial and energy savings.

In one aspect of the present invention, a switching current source is used for driving the injection laser diode in the optic preamplifier such that inefficient linear drivers are replaced. The current injection laser diodes used in many prior art devices are inefficient and operate on the order of 300 mW, to deliver the optic power to an erbium-doped gain element.

30 Some injection laser diode drivers use a linear pass transistor to deliver the regulated current to the injection laser diode. This results in a constant voltage across and constant current through the device, resulting in a large amount of dissipated

power, and in some instances, nearly 90% occurring at the pass transistor.

The present invention allows a clean current to be delivered to the injection laser diode from a 5 switching pass transistor, which is alternatively operated in the "full on," then the "full off" mode. When in the "full on" mode, there is no voltage across the transistor. When in the "full off" mode, no current flows through the transistor. As a result, the 10 switching pass transistor dissipates a reduced amount of power. By allocating the switcher operating parameters based on characteristics of the injection laser diode and the erbium gain element, the switcher noise is maintained in a manner consistent with the 15 high performance of the optical amplifier. Expected efficiency improvements are reduction of the pass transistor power to approximately 15% of total driver power, and total net efficiencies, including the injection laser diode, in the range of up to about 30%. 20 This allows additional fibers to be placed in cables.

The present invention also provides a wavelength division multiplexed and low power optically amplified receiver that is fully integrated and optimized with high sensitivity. It incorporates low 25 power engineering and has a customized high efficiency pump laser driver as described before, and thermo-electric coolerless operation of the pump laser. It allows silicon based chip technology in the receiver. In one aspect of the invention, as a 30 non-limiting example only, it is optimized and integrated for achieving high sensitivity in the form of eight different channels at 2.488 Gb/s channels based at 100 GHz (0.8 nM).

The receiver, in one aspect of the invention, 35 uses a single input fiber with multiple wavelengths as

described. It has a low noise, gain flattened erbium doped fiber amplifier that acts as a preamplifier, followed by a low loss demultiplexer with minimal variation in channel-to-channel output power. A 5 receiver array then follows and includes in each receiver a PIN detector and high speed electronics.

As noted before, the bandwidth of a single channel or wavelength fiber optic telecommunication link is limited by the high-speed electronics required 10 at the transmitter and receiver. Although various channel data rates are known, the present invention will be described relative to data rates of about 2.5 Gb/s. Naturally, the design can be used with increased data rates. Some state-of-the-art optical 15 receivers for single channel fiber optic telecommunication links operate at 2.488 Gb/s, and are limited to operating at a bit/error ratio of 1×10^{-11} at incident optical powers of -34 dBm. Wavelength division multiplexing (WDM) increases the bandwidth of 20 a fiber optic telecommunications link without requiring an increase in the speed of electronics. This technique multiplexes multiple channels and wavelengths, each modulated at, as a non-limiting example, 2.488 Gb/s, onto a single fiber. This 25 aggregate bit rate of the fiber now becomes $N \times 2.488$ Gb/s where $N=2, 3, 4, \dots$. At the receiver, the optical channels are separated and demultiplexed and sent to their individual 2.488 Gb/s receivers.

The demultiplexing process is not ideal and 30 optical losses are incurred, thus reducing the overall receiver sensitivity. This translates to shorter transmission lengths. By incorporating the optic preamplifier based on the erbium doped fiber technology of the present invention, the demultiplexer losses are 35 overcome and can increase the signal level well above

the receiver noise floor and increase the receiver sensitivity. The erbium doped fiber amplifier technology allows the use of PIN detectors in place of avalanche photo diodes as an optical-to-electrical converter. By optimizing each of the individual components and incorporating them into a single unit, the invention not only increases transmission distances over currently available technology, but also reduces the volume of equipment-rack space.

10 Referring now to the drawing figures, a more detailed description of the invention follows.

FIG. 1 illustrates a wavelength division multiplexed optical network **10** where various signals $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ come through a plurality of optical fiber channels **12** as fiber optic lines into a trunk optical fiber **14** and into an in-line erbium doped fiber amplifier repeater **16** to a star coupler **18**. Different signal branches **20** (ON-1, . . . ON-N) extend from the star coupler **18**, where one branch (or channel) is illustrated as having optical receiver **28**, and a low noise erbium doped fiber amplifier **22** and an optical bandpass tunable filter **24** followed by a photo receiver **26**, such as working at 2.5 Gb/s.

FIG. 2 illustrates at **30** an optically amplified receiver of the present invention contained in housing, or in another aspect of the invention, on a printed circuit card assembly **31**. In one aspect, components are mounted on a single printed circuit card assembly, which can be mounted in one housing, and forming an integral receiver assembly. Although the description will proceed relative to a description with non-limiting data rates of 2.5 Gb/s, it should be understood by all those skilled in the art that the invention can be applied to different data rates.

As shown in FIG. 2, the signal P_s enters the erbium doped fiber preamplifier **32**, acting as an optical preamplifier. The relative operating parameters for the illustrated preamplifier **32**, tunable 5 bandpass filter circuit **34** and optical-to-electrical conversion circuit **36**, are illustrated relative to the appropriate blocks. The bandpass filter receives the signal from the optical preamplifier, selects a single channel, and filters out noise produced by the optical 10 preamplifier in a manner known to those skilled in the art.

In one aspect of the invention, the tunable bandpass filter circuit **34** of the present invention includes a power splitter **40** and optical bandpass 15 tunable filters **42**, as shown in FIGS. 4 and 5, where the power splitter **40** is shown as cascaded 3-dB couplers **44**. Although this illustrates only one type of power splitter/optical bandpass tunable filter and demultiplexer that can be used with the present 20 invention, it should be understood that different types of circuits can be used with the present invention.

In one aspect of the present invention, the optical-to-electrical conversion circuit **36** includes a PIN detector (diode) **50**, followed by a low-noise 25 electrical amplifier **52**. An electronic limiting amplifier **54** works in conjunction with decision circuit **56** and allows data recovery and reshapes electrical communication signals, while a clock recovery circuit **58** allows recovery of clock signals and retiming of 30 electrical communication signals.

FIG. 3 illustrates the low power laser driver circuit **60** of the present invention, which is used for driving the optical preamplifier and receiver assembly. The five volt supply voltage input is standard with

many electronic circuits. The laser driver circuit 60 includes an injection laser diode 62 that is, in one aspect of the present invention, a quantum efficiency injection laser diode (HQEILD). A current source 5 control loop circuit 64 is connected to the injection laser diode 62 and establishes a fixed current through the injection laser diode. This current source control loop circuit 64 has a voltage switcher circuit chip 66 connected to the injection laser diode, within the 10 current source control loop circuit, and is adapted to receive the fixed supply voltage of five volts and convert inductively the supply voltage down to a forward voltage, to bias the laser injection diode and produce an optical output having minimized power 15 losses.

This voltage switcher circuit chip 66 is monolithically formed as a single circuit chip, and is used as a high efficiency voltage converter as shown in FIG. 3.

20 The current source control loop circuit 64 includes the high efficiency current source 70, acting as a low noise current source and the current control circuit 72. These circuits are all contained within one housing, and in one aspect, on a printed circuit 25 card assembly 74 that includes the receiver components, including the preamplifier, tunable bandpass filter circuit and optical-to-electrical conversion circuit.

The schematic circuit diagram shows various power and voltage, as well as current parameters. In 30 this non-limiting example, at 260 milliwatts and at five volts DC, there is a 35 decibel optical gain, with one channel as a design goal. There could be a 266 milliwatt DC for eight channels, and 220 milliwatts DC achieved. The Bragg grating 73 is operatively

connected to the injection laser diode **62**, and is operative by principles known to those skilled in the art. The Bragg grating **73** is configured for receiving the optical output and stabilizing the optical wavelength.

FIG. 5 illustrates a graph showing the log of base 10 for the bit error rate (BER) versus the input optical power (in dBm). The square dots represent a PIN only receiver, without optical amplifier, while the triangular dots represent the optically amplified PIN receiver of the present invention. There is illustrated on the graph an 18 decibel improvement in system sensitivity using the optically preamplified receiver of the present invention.

15 This application is related to copending
patent applications entitled, "**LOW POWER LASER DRIVER**"
which is filed on the same date and by the same
assignee and inventors, the disclosure which is hereby
incorporated by reference.

20 Many modifications and other embodiments of
the invention will come to the mind of one skilled in
the art having the benefit of the teachings presented
in the foregoing descriptions and the associated
drawings. Therefore, it is to be understood that the
25 invention is not to be limited to the specific
embodiments disclosed, and that the modifications and
embodiments are intended to be included within the
scope of the dependent claims.